The Comprehensive Ring Current Model (CRCM)

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Outline

❖ The **C**omprehensive **R**ing **C**urrent **M**odel (CRCM)

- History
- Model logic
- Model formulation
- Numerical schemes
- Code architecture
- Model input/output

❖ Model the ring current enhancements during the storm on 12 August 2000.

❖ Model the O+ enhancements during a substorm

❖ MHD-CRCM-Ionosphere coupling and challenges

The Comprehensive Ring Current Model (CRCM)

Fok Ring Current Model
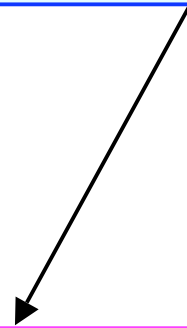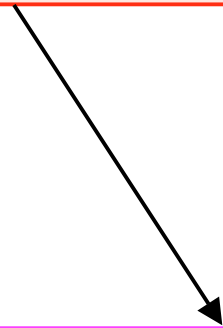Empirical E field
Full pitch-angle distribution

Rice Convection Model (RCM)
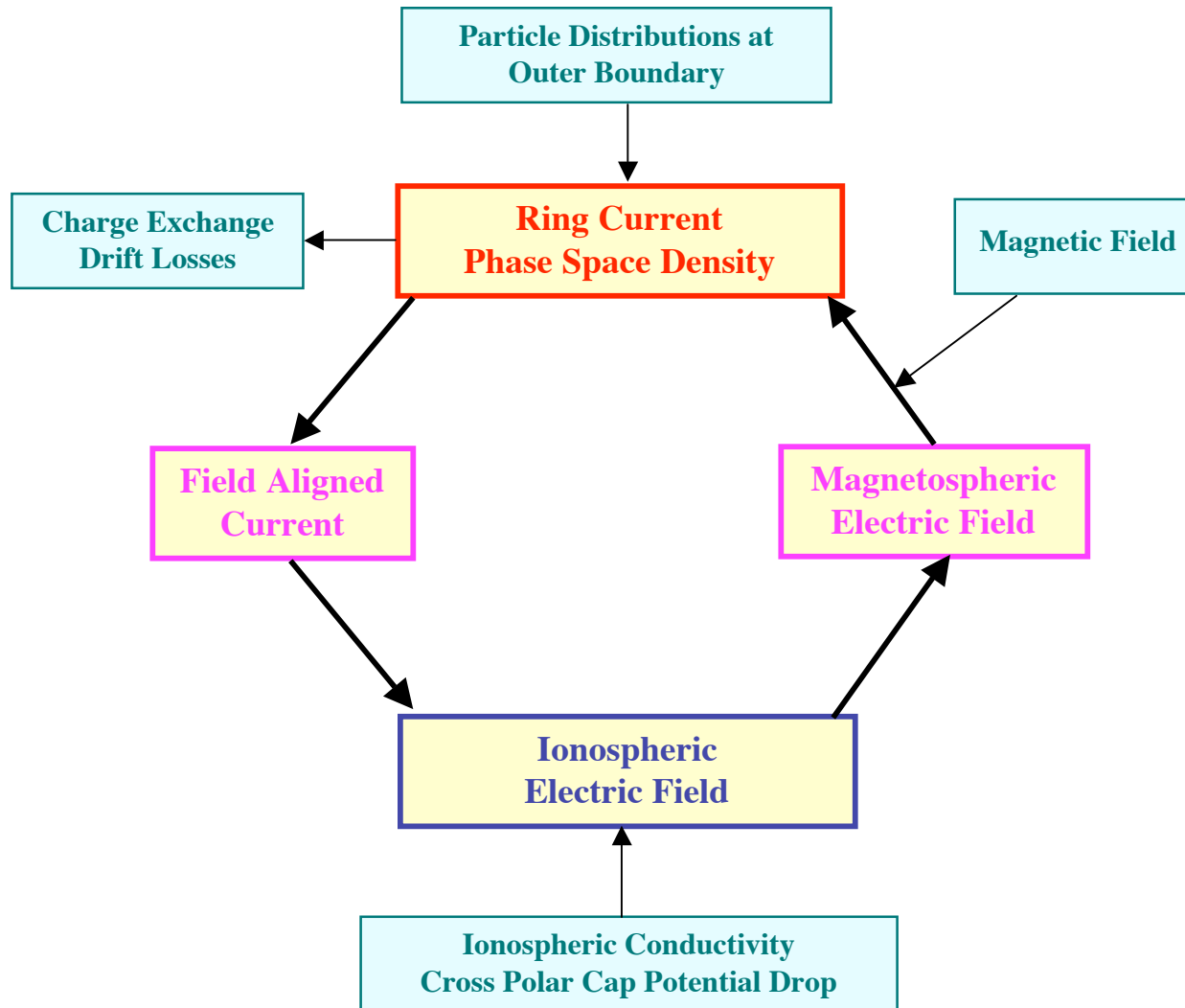Self-consistent E field
Isotropic pitch-angle distribution

Comprehensive Ring Current Model (CRCM)
Self-consistent E field
Full pitch-angle distribution

The Comprehensive Ring Current Model: Model Logic

Particle Distributions at Outer Boundary

Ring Current Phase Space Density

Charge Exchange Drift Losses

Magnetic Field

Field Aligned Current

Magnetospheric Electric Field

Ionospheric Electric Field

Ionospheric Conductivity Cross Polar Cap Potential Drop

The Comprehensive Ring Current Model: The Equations

Equation of ring current ion distribution

$$\frac{\partial f_s}{\partial t} + \langle \dot{\lambda}_i \rangle \frac{\partial f_s}{\partial \lambda_i} + \langle \dot{\phi}_i \rangle \frac{\partial f_s}{\partial \phi_i} = -v\sigma_s \langle n_H \rangle f_s - \left(\frac{f_s}{0.5\tau_b} \right)_{\text{losscone}}$$

$f_s = f_s(t, \lambda_i, \phi_i, M, K)$: phase space density of ring current ion

λ_i , ϕ_i : magnetic latitude and local time at ionosphere

M : magnetic moment

K : longitudinal invariant

$\langle \dot{\lambda}_i \rangle, \langle \dot{\phi}_i \rangle$: drift velocities (convection + magnetic drift + corotation)

σ_s : charge exchange cross section of s and H

$\langle n_H \rangle$: bounce - averaged H density

τ_b : bounce period

Equation of ionospheric potential

$$\nabla \bullet \left(-\overleftrightarrow{\Sigma} \bullet \nabla \Phi \right) = J_{\|i} \sin I$$

Φ : ionospheric potential

$\overleftrightarrow{\Sigma}$: conductance tensor

I : magnetic dip angle

$J_{\|i}$: parallel current at ionosphere $= \dfrac{1}{r_i^2 \cos \lambda_i} \sum_s \dfrac{\partial \eta_s}{\partial \lambda_i} \dfrac{\partial E_s}{\partial \phi_i} - \dfrac{\partial \eta_s}{\partial \phi_i} \dfrac{\partial E_s}{\partial \lambda_i}$

where $\eta_s = 4\sqrt{2}\pi \, m_s^{3/2} f_s \, M^{1/2} \Delta M \, \Delta K$

The Comprehensive Ring Current Model: Numerical Schemes

$$\frac{\partial f_s}{\partial t} + \langle \dot{\lambda}_i \rangle \frac{\partial f_s}{\partial \lambda_i} + \langle \dot{\phi}_i \rangle \frac{\partial f_s}{\partial \phi_i} = -v\sigma_s \langle n_H \rangle f_s - \left(\frac{f_s}{0.5\tau_b} \right)_{\text{losscone}}$$

Fractional Step Approach:

$$f_s^n = f_s(t_n) \longrightarrow f_s^{n+1} = f_s(t + \Delta t) = f_s(t_{n+1})$$

$f_s^{n+1/3} = D_1\left[f_s^n \right]$ $\qquad$ $\frac{\partial f_s}{\partial t} + \langle \dot{\lambda}_i \rangle \frac{\partial f_s}{\partial \lambda_i} + \langle \dot{\phi}_i \rangle \frac{\partial f_s}{\partial \phi_i} = 0$ $\qquad$ Conservation Law, Flux Limited Scheme

$f_s^{n+2/3} = D_2\left[f_s^{n+1/3} \right]$ $\qquad$ $\frac{\partial f_s}{\partial t} = -v\sigma_s \langle n_H \rangle f_s$ $\qquad$ Exact solution, $f_s^{n+2/3} = f_s^{n+1/3} \exp\left(-v\sigma_s \langle n_H \rangle \Delta t \right)$

$f_s^{n+1} = D_3\left[f_s^{n+2/3} \right]$ $\qquad$ $\frac{\partial f_s}{\partial t} = -\left(\frac{f_s}{0.5\tau_b} \right)_{\text{losscone}}$ $\qquad$ Exact solution, $f_s^{n+1} = f_s^{n+2/3} \exp\left(-\frac{\Delta t}{0.5\tau_b} \right)$
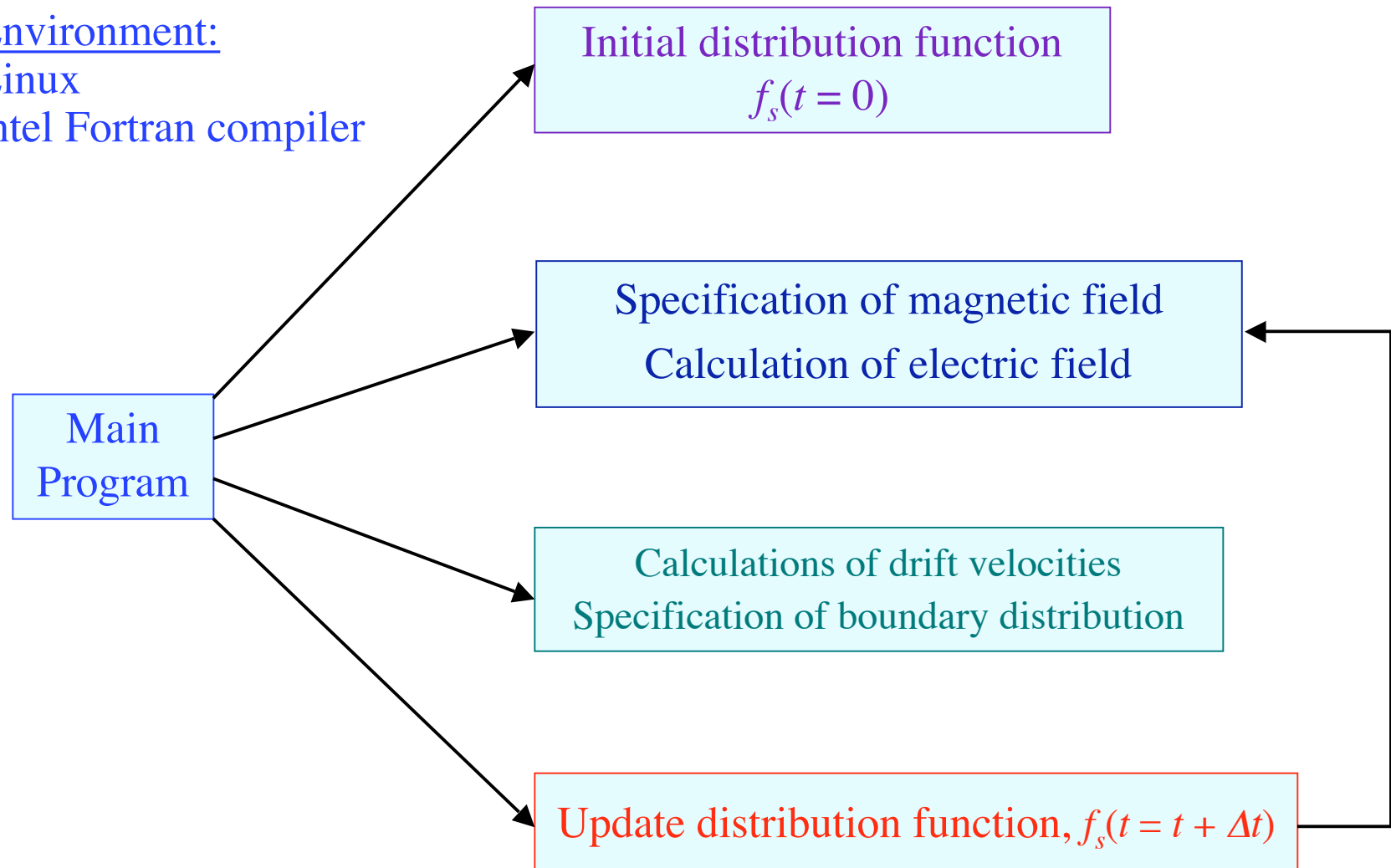
The Comprehensive Ring Current Model: Code Architecture
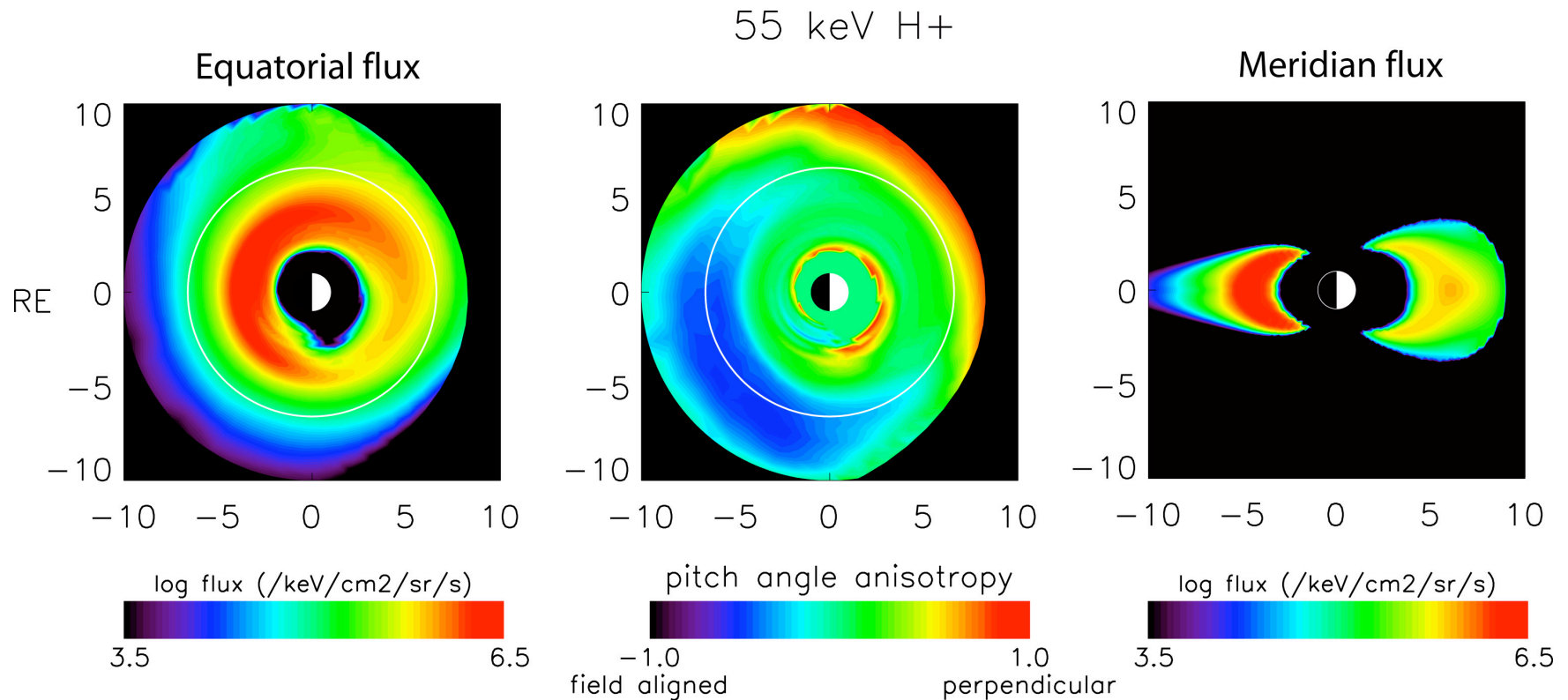
Environment:
Linux
intel Fortran compiler

Initial distribution function
$$f_s(t = 0)$$

Specification of magnetic field

Calculation of electric field

Main
Program

Calculations of drift velocities
Specification of boundary distribution

Update distribution function, $f_s(t = t + \Delta t)$

The Comprehensive Ring Current Model: The Input

❖   Dst, Kp: Kyoto University Geomagnetic Data Service

❖   Shifted solar wind, IMF data: ACE or WIND satellite

❖   Distribution at the nightside boundary (8-10 RE):
    MHD or
    Nps(t) = 0.025 Nsw(t-3hr) + 0.395   cm^-3
    kT(t) = 0.019 Vsw(t-3hr) - 3.65   keV

❖   Magnetic field model: T96, T04 or MHD models

❖   Ionospheric potential at polar boundary: Weimer model

❖   Conductance: background conductance + auroral
    conductance (Hardy model).

The Comprehensive Ring Current Model: The Output 1

CRCM Output: 3-dimensional Ion Flux
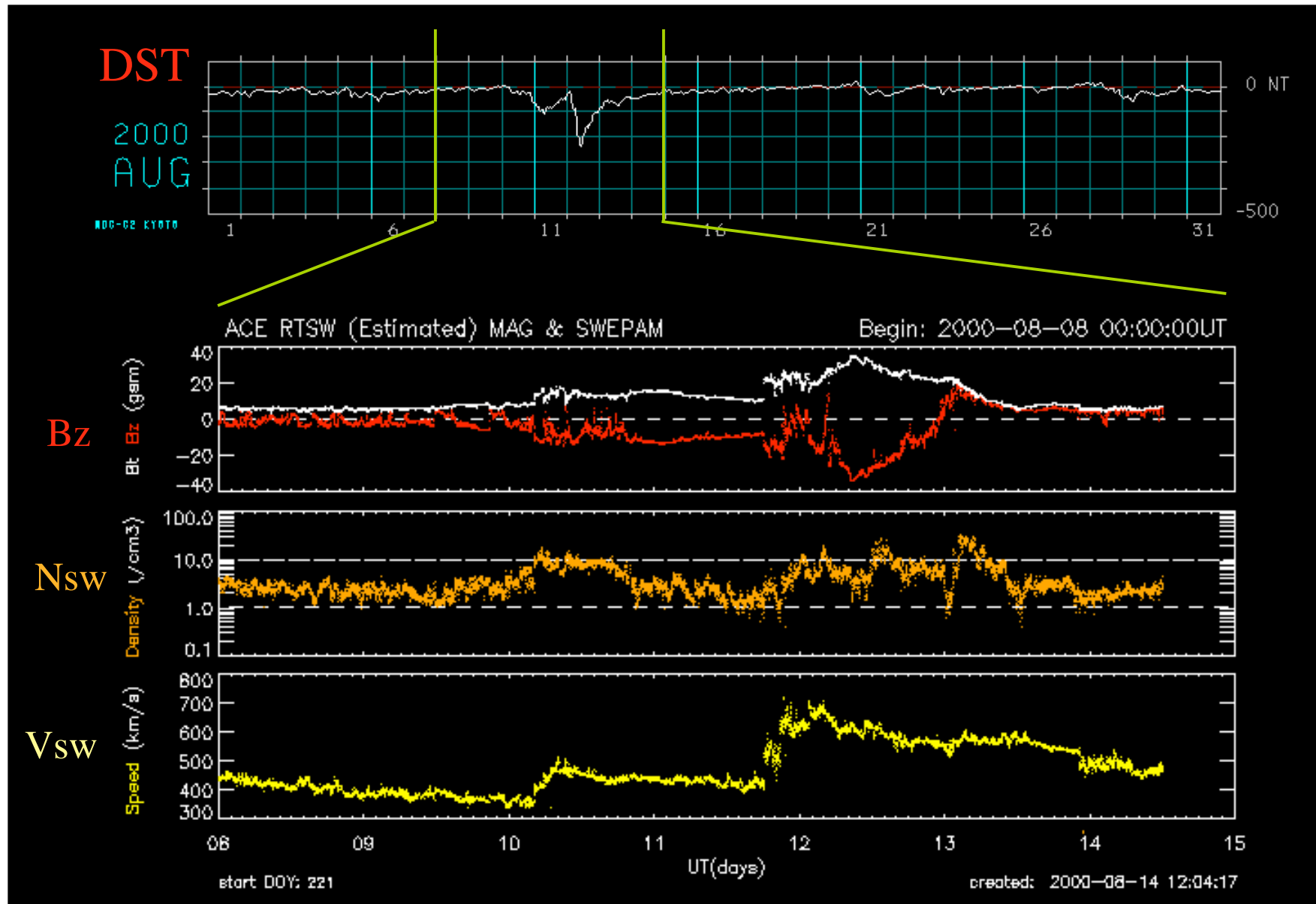from 1 to 300 keV at all pitch angles

55 keV H+

The Comprehensive Ring Current Model: The Output 2

Sun

magnetic latitude (degree)

Birkeland current (microAmp/m2)

−1.0
current away from ionosphere

1.0
current into ionosphere

Sun

RE
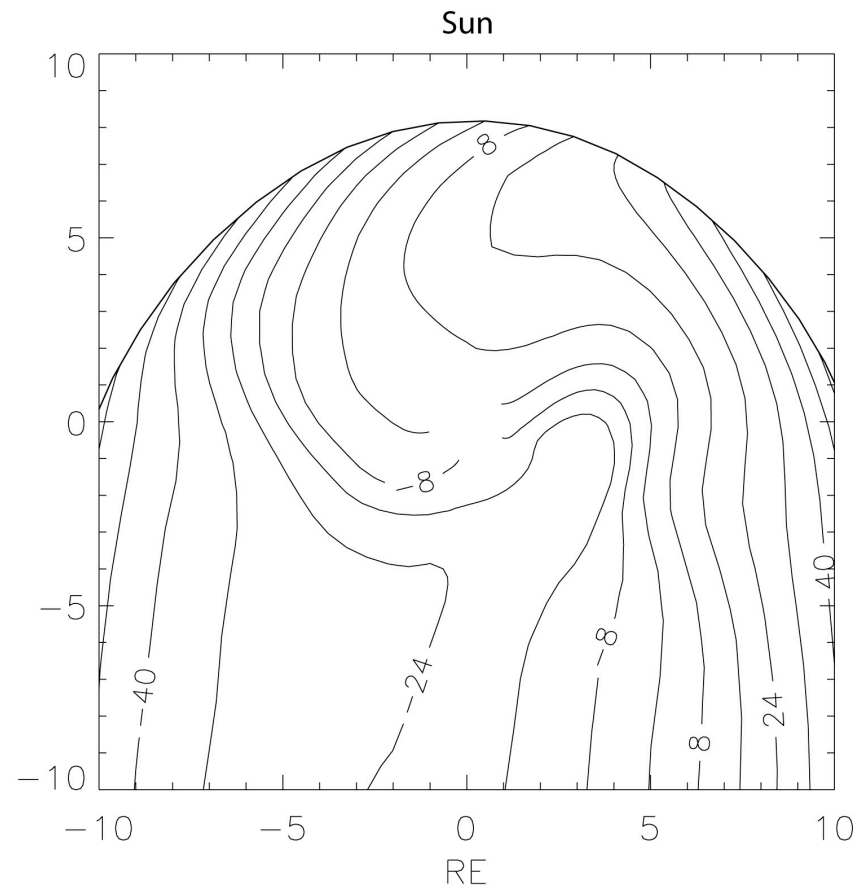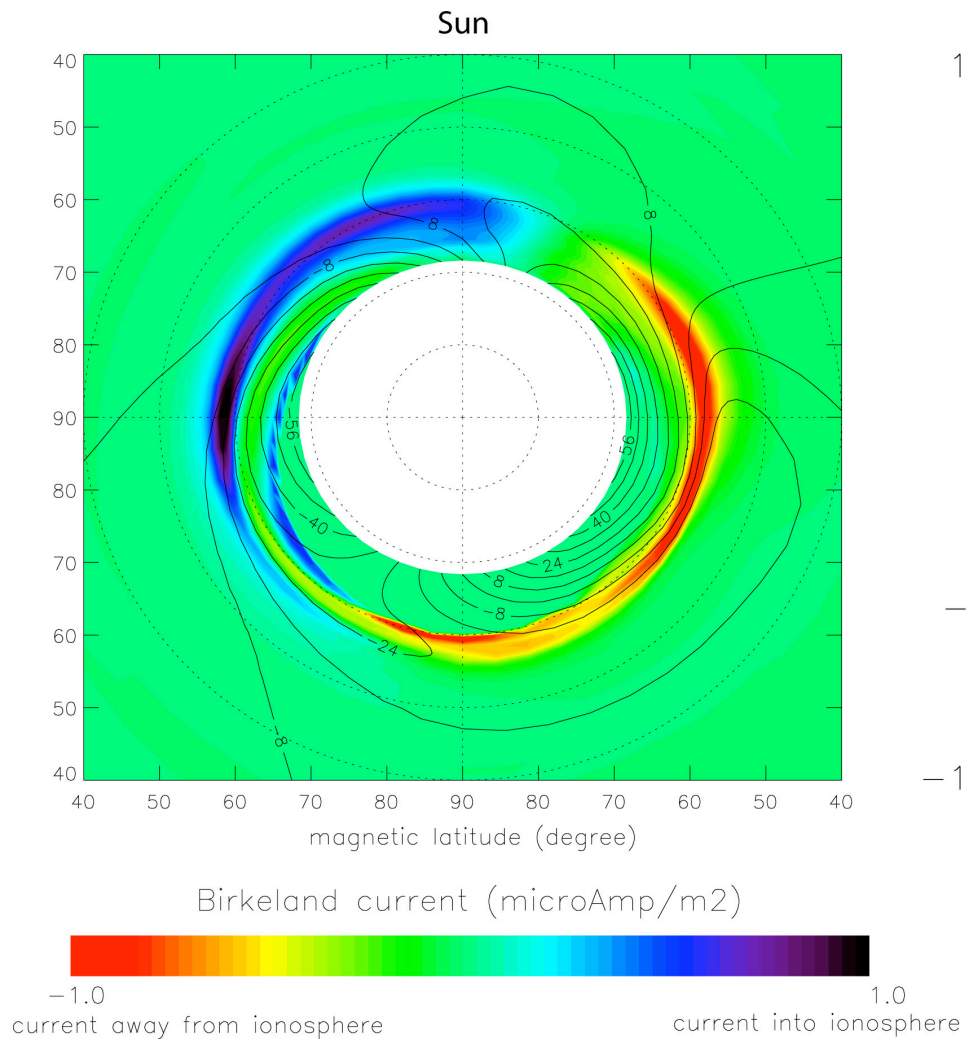
Equatorial Potential

The Great Magnetic Storm in August 2000
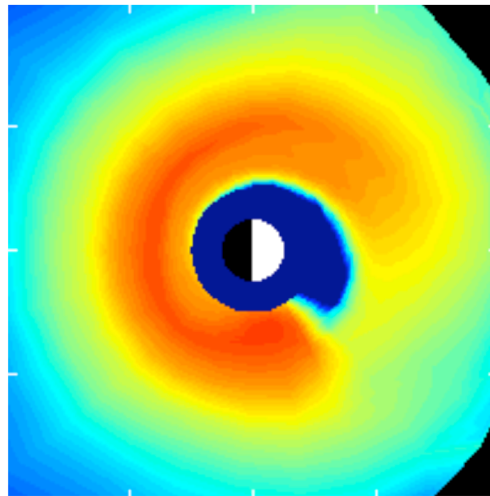
CRCM Reproduced the Post-midnight Enhancement
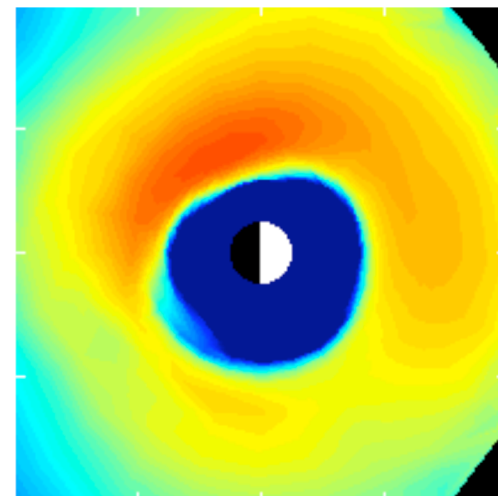
09:00 UT, 12 August 2000
32 keV H$^+$

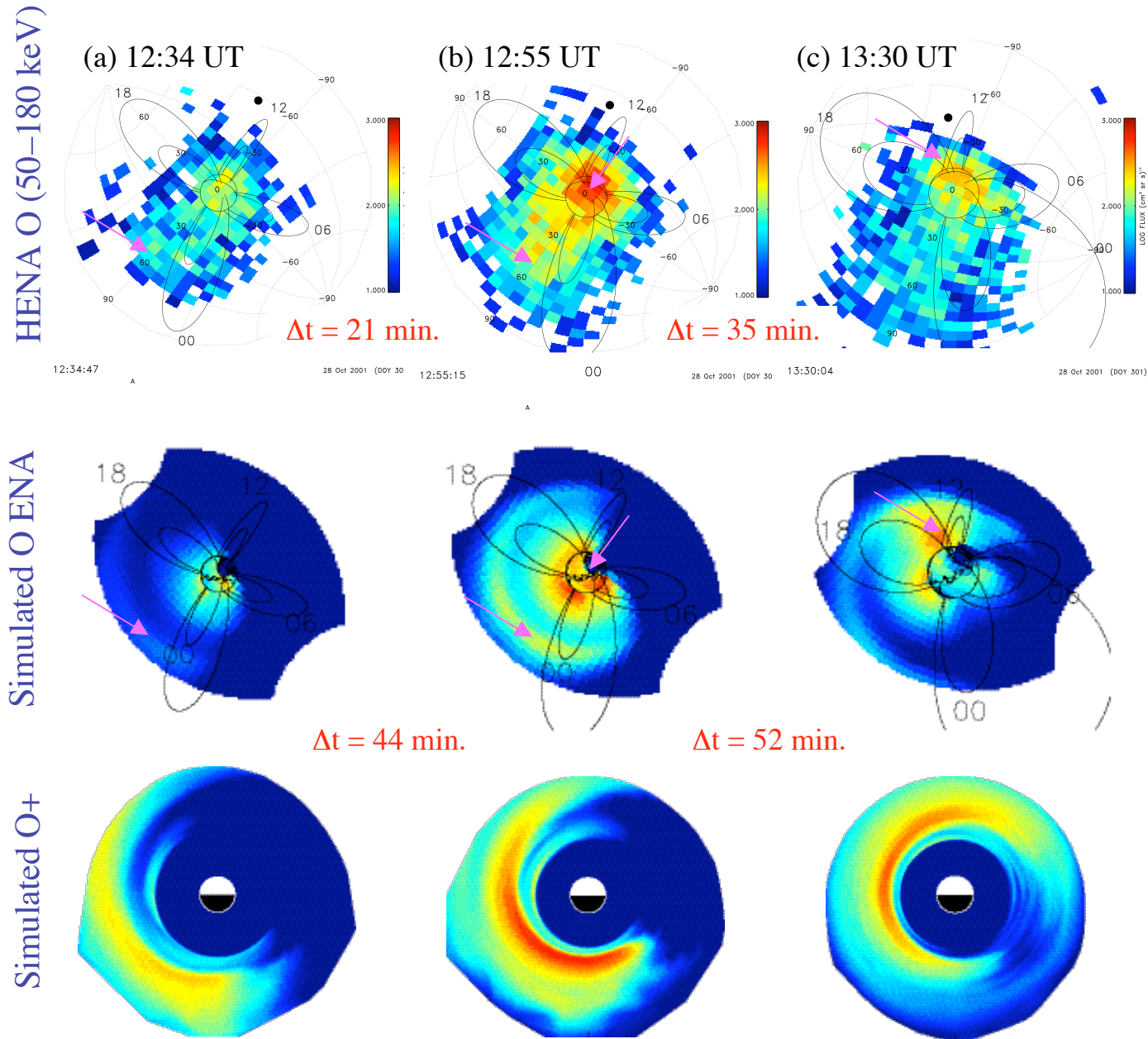Inverted HENA H+ flux   Simulated flux from CRCM   Simulated flux from Weimer
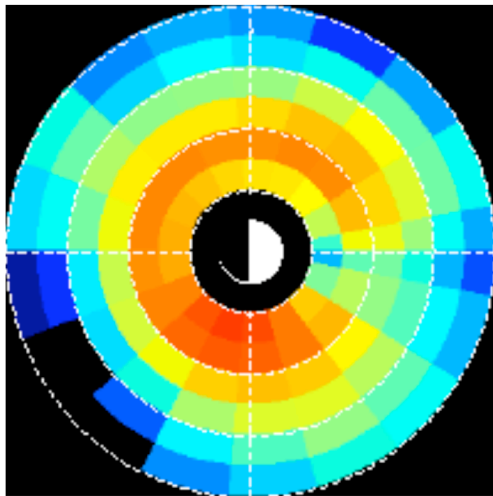
Simulation of H+ and O+ Distributions During a Substorm

- A modeled substorm by the Lyon-Fedder-Mobarry (LFM) model.
- Tracing trajectories of 100 millions H+ and O+ released from the solar wind, polar region and the auroral zone in the LFM fields.
- From the test-particle calculations, H+ and O+ characteristics (density and velocity) in each 1 RE^3 volume element of the magnetosphere are established.
- Ion distributions in the inner magnetosphere are calculated by the Comprehensive Ring Current Model (CRCM) with the boundary conditions specified by the test-particle runs.
- Energetic Neutral Atom (ENA) emissions are calculated from the ion fluxes output from the CRCM.
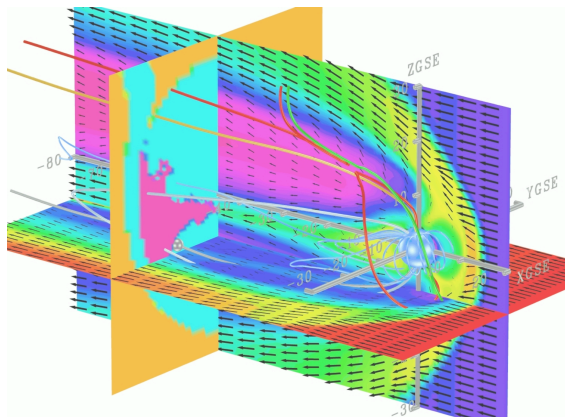
LFM MHD model ---> Delcourt's particle code ---> CRCM ---> Ion and ENA fluxes

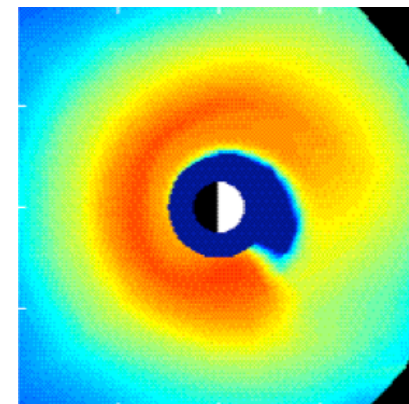# LFM-CRCM Reproduce the O+ Enhancement During a Substorm

HENA O (50–180 keV)

(a) 12:34 UT   (b) 12:55 UT   (c) 13:30 UT

Δt = 21 min.   Δt = 35 min.

12:34:47   28 Oct 2001 (DOY 30)   12:55:15   28 Oct 2001 (DOY 30)   13:30:04   28 Oct 2001 (DOY 301)

LOG FLUX (cm² sr s)⁻¹

Simulated O ENA

Δt = 44 min.   Δt = 52 min.

Simulated O+

CRCM Coupling with the OpenGGCM
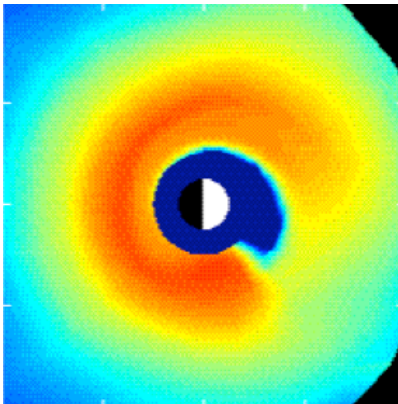
OpenGGCM

CRCM

B, V, Φ_i, n, T →

← $P(P_{\parallel}, P_{\perp}), J_{\parallel}$

B: magnetic field
V: flux tube volume per unit flux
Φ_i : Ionospheric potential
n: average density in the flux tube
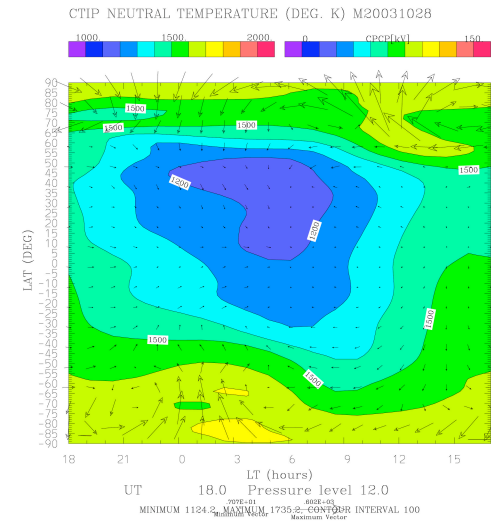T: average temperature in the flux tube

P: pressure from ring current particles
$J_{\parallel}$: field aligned current

CRCM

CTIPe

$J_{\|}, \phi_{pp}, L_{pp}$

$J_{\|}$: field aligned current

ϕ_{pp} : energetic particle precipitation

L_{pp} : plasmapause location

$$\frac{D_{\perp} N}{Dt} = \frac{F_N + F_S}{B_i} \qquad (7)$$

where D/Dt is the convective derivative in the $E\times B$ frame of the flux tube, N is the total ion content per unit magnetic flux, F_N and F_S are the ionospheric fluxes in or out of the flux tube at northern and southern ionospheres, and B_i is the magnetic field at the ionospheric foot points of the flux tube. The equatorial plasma density is assumed to be equal to the average density in the flux tube.

The net flux of plasmas in or out of a flux tube depends on the instantaneous content of the flux tube. The particle flux on the dayside, F_d, is given by:

$$F_d = \frac{n_{sat} - n}{n_{sat}} F_{max} \qquad (8)$$

where n_{sat} is the saturation density [*Carpenter and Anderson, 1992*], n is the plasma density in the flux tube, and F_{max} is the limiting flux from the ionosphere [*Chen and Wolf, 1972*]. The nightside flux, F_n, is approximated by:

$$F_n = -\frac{N B_i}{\tau} \qquad (9)$$

where τ is the downward diffusion lifetime on the nightside, which is assumed to be 10 days.

Plasmasphere Dynamics Driven by CRCM Electric Field

[EUV images]

DGCPM/CRCM plasmasphere density
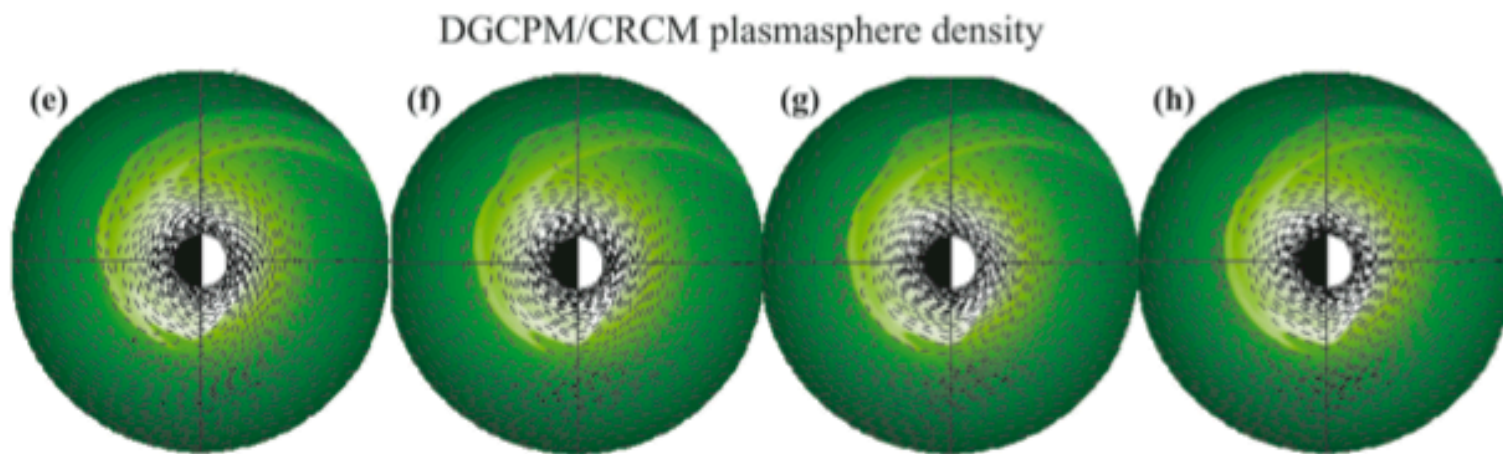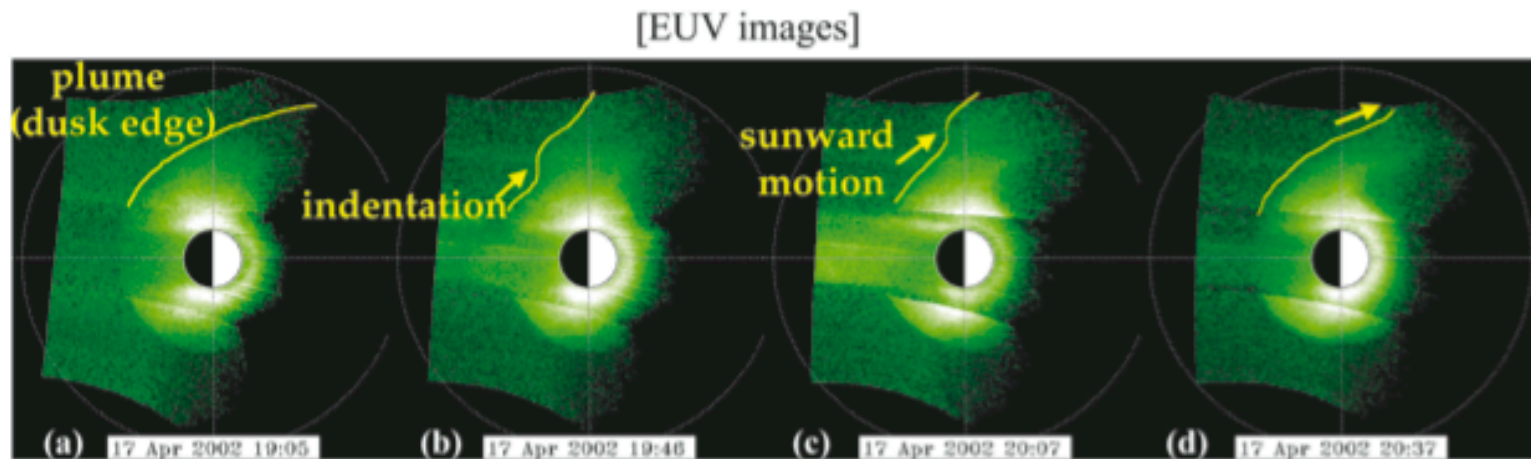
Challenges in Code Coupling

❖ Potential solver in the OpenGGCM must be extended to low latitude to ~ 12˚.

❖ -

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